The structure of the strange sea of the proton

C. Ávila,* L. Salazar-Garcia, and J.C. Sanabria†
Departamento de Física, Universidad de los Andes, A.A. 4976, Bogota, D.C., Colombia

J. Magnin‡
Centro Brasileiro de Pesquisas Físicas, Rua Dr. Xavier Sigaud 150, Urca 22290-180, Rio de Janeiro, Brazil

In this work we study the strange sea of the proton using a version of the Meson Cloud Model containing both, efective and perturbative degrees of freedom. We construct the s and $\bar{s}$ parton distributions functions at the initial energy scale, Q_0^2, where QCD evolution starts. The initial s and $\bar{s}$ pdfs depend on a number of parameters which we fix by comparison to parameterizations of the strange sea of the nucleon obtained in a recent global fit to experimental data, allowing for a $s-\bar{s}$ asymmetry. We show that the model describes well the strange sea of the proton and argue that it can be a phenomenologically motivated alternative to the usual input parameterizations used in fits to experimental DIS data.

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I. INTRODUCTION

The composite nature of hadrons in term of quark and gluon degrees of freedom is today firmly stablished. It is also firmly believed that the internal dynamics of hadrons is determined by the strong interactions between quarks and gluons, as governed by Quantum Chromodynamics (QCD). However, a detailed theoretical description of the hadron structure is still missing because QCD can only be solved in the perturbative regime, corresponding to the short distance domain probed in hard collisions, whereas the long distance part of the interaction requires a non-perturbative treatment usualy supplied by effective models, latice simulations, etc. It is worth noting that is just the long distance part of the interaction which is responsible for the hadron as a bound state of quarks and gluons. Indeed, hadrons are made up of a fixed number of valence quarks plus a varying number of sea quark-antiquark pairs and gluons, being these last the "glue" which keeps valence quarks together forming a hadron. As a matter of fact, the sea $q-\bar{q}$ pairs and gluons which bring together the valence quarks into a bound state are the so-called *intrinsic* sea [1], which has to be distinguished from the *extrinsic* sea generated by QCD evolution and consequently, dependent on the energy scale Q^2.

From an experimental point of view, the structure of nucleons is by far the best known hadron structure, existing today a variety of parton distribution function (pdf) parameterizations extracted from data. Although the analysis of the existing data has confirmed the impresive success of the Quark Parton Model and the Dokshitzer-Grivov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations [2] when describing the nucleon structure, in the Bjorken regime, in terms of pdf's given as a function of x, the fraction of the nucleon momentum carried by partons, and Q^2, the energy scale which in Deep Inelastic Scattering (DIS) experiments is identified with the 4-momentum transfer between the lepton and the nucleon, several questions remain still unsolved. Among them, what is the functional form - and why - of the valence and sea quark and gluon pdf's at the energy scale Q_0^2 where QCD evolution starts; what is the value of the initial Q_0^2 energy scale; what is the structure of the so-called intrinsic sea of $q-\bar{q}$ pairs and gluons; etc. Of course, finding answers to these questions requires to deal with the long distance - confining - realm of QCD, thus, as long as there is no solution of QCD in the low Q^2 regime, we have to rely on effective models.

Furthermore, the structure of the nucleon's intrinsic sea of quarks and gluons reflects the dynamics of non-perturbative QCD. In fact, the form of the initial pdfs at the Q_0^2 initial scale, as well as the relative abundance of the different quark flavors are the footprint of subtle non-perturbative QCD dynamical effects. Notice, for instance, that the experimentally observed $\bar{d}/\bar{u}$ asymmetry [3] and the violation of the Gottfried sum rule (GSR) [4] cannot be described in terms only of perturbative QCD and gluon splitting [5], as the ratio $\bar{d}/\bar{u}$ would became equal to one, due to the equal probability of gluon splitting into $d\bar{d}$ or $u\bar{u}$ pairs. The distribution of strange and anti-strange quarks in the nucleon sea is another nontrivial aspect of the nucleon structure. From the experimental side, some evidence has been found on a possible $s-\bar{s}$ asymmetry coming from global fits to data [6]. Notice that there is no fundamental symmetry preventing $s(x) \neq \bar{s}(x)$ in the nucleon, provided that $\int_0^1 [s(x)-\bar{s}(x)] = 0$. On the theoretical side, speculations about a possible $|KH\rangle$ component in the nucleon wave function, where K, H are virtual Kaon and Hyperon states, leading to a $s-\bar{s}$ asymmetry, date since 1987, with the pionering work by Signal and Thomas [7]. Since then on, several models have been proposed in the

*Electronic address: cavila@uniandes.edu.co
†Electronic address: jsanabri@uniandes.edu.co
‡Electronic address: jmagnin@cbpf.br

literature [8, 9], with different predictions. It is worth to note also that a $s-\bar{s}$ asymmetry in the nucleon is generated perturbatively starting at Next-to-Next to Leading Order (NNLO) [10] because at this order the splitting functions P_{qq} and $P_{q\bar{q}}$ are different. That asymmetry, although very small, should compete with the $s-\bar{s}$ asymmetry generated by the non-perturbative dynamics of the bound state.

In this paper we shall investigate to what extent a non-perturbatively generated $s-\bar{s}$ asymmetry can describe the strange sea asymmetry found in recent global fits to experimental data. In order to do that, in Section II we will revise a model for the generation of the intrinsic $s/\bar{s}$ sea of the nucleon, following in Section III with a comparison of the model with experimental data and recent parameterizations of the strange sea of the proton. Section IV will be devoted to further discussion and conclusions.

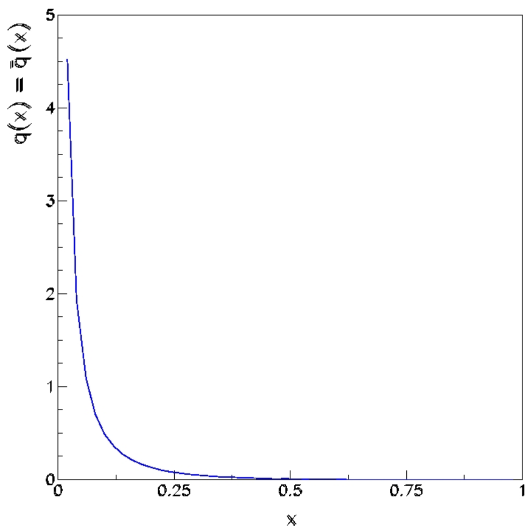

FIG. 1: Sea $q/\bar{q}$ parton distribution in the proton as given by Eq. 2.

II. THE NON-PERTURBATIVE STRANGE SEA OF THE PROTON

We start by considering a simple picture of the nucleon in the infinite momentum frame as being formed by three dressed valence quarks - *valons*, $v(x)$ - which carry all of its momentum [11],

$$
\begin{aligned}
v_u(x) &= \frac{2}{\beta(a_u+1,b_u+1)} x^{a_u}(1-x)^{b_u} , \\
v_d(x) &= \frac{1}{\beta(a_d+1,b_d+1)} x^{a_d}(1-x)^{b_d} , \qquad (1)
\end{aligned}
$$

with x the fraction of momentum carried by the valon with respect to the proton.

In the framework of the Meson Cloud Model (MCM), the nucleon can fluctuate to a meson-baryon bound state carrying zero net strangeness. As a first step in such a process, we may consider that each valon can emit a gluon which, before interacting, decays perturbatively into a $s\bar{s}$ pair. The probability of having such a perturbative $q\bar{q}$ pair can be computed in terms of Altarelli-Parisi splitting functions [2]

$$
\begin{aligned}
P_{gq}(z) &= \frac{4}{3}\frac{1+(1-z)^2}{z}, \\
P_{qg}(z) &= \frac{1}{2}\left(z^2+(1-z)^2\right) . \qquad (2)
\end{aligned}
$$

These functions have the physical interpretation as the probability of gluon emision and $q\bar{q}$ creation with momentum fraction z from a parent quark or gluon respectively. Hence,

$$
q(x,Q_0^2) = \bar{q}(x,Q_0^2) = N\frac{\alpha_{st}^2(Q_0^2)}{(2\pi)^2} \times \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) \int_y^1 \frac{dz}{z} P_{gq}\left(\frac{y}{z}\right) v(z) \quad (3)
$$

is the joint probability density of obtaining a quark or anti-quark coming from subsequent decays $v \to v+g$ and $g \to q+\bar{q}$ at some fixed low Q_0^2. In eq. (3), N is a normalization constant which should scale with the masses of the flavors being created so that to a heavier flavor, corresponds a smaller N. Since the valon distribution does not depend on Q_0^2 [11], the scale dependence in eq. (3) only exhibits through the strong coupling constant α_{st}. The range of values of Q_0^2 at which the process of virtual pair creation occurs in this approach is typically below 1 GeV^2. A tipical sea quark distribution obtained from eq. (3), is shown in Fig. (1), where, in the spirit of keeping as simple as possible the description of the process , whe have assumed $v_u = v_d$ and used $a_u = a_d = 0.5$, $b_u = b_d = 2$ in eqs (1).

Once a $s\bar{s}$ pair is produced, it can rearrange itself with the remaining valons so as to form a most energetically favored Kaon-Hyperon bound state. In order to obtain the Kaon and Hyperon probability densities in the $|KH\rangle$ component of the proton wave function, the well known approach of the recombination model [12] has been used [8]. Notice however that the Kaon and Hyperon probability densities obtained in this way can be represented in terms of the simple forms [8]

$$
\begin{aligned}
P_K(x) &= \frac{1}{\beta(a_K+1,b_K+1)} x^{a_K}(1-x)^{b_K} , \\
P_H(x) &= \frac{1}{\beta(a_H+1,b_H+1)} x^{a_H}(1-x)^{b_H} , \qquad (4)
\end{aligned}
$$

which are both properly normalized to unity, as it should be for a bound state of one Kaon and one Hyperon and in order to cope with the zero net strangeness of the proton. These forms are also consistent with the valon model for a hadron made of two partons bound state.

The coefficients a_K, b_K, a_H, b_H in eqs. (4) are not independent. In fact, as the Kaon and Hyperon have to exhaust the momentum of the proton, then

$$\int_0^1 dx\,[xP_H(x) + xP_K(x)] = 1\ , \tag{5}$$

giving the constraint

$$\frac{\Gamma(a_{\rm K}+b_{\rm K}+2)\Gamma(a_{\rm K}+2)}{\Gamma(a_{\rm K}+1)\Gamma(a_{\rm K}+b_{\rm K}+3)} + \frac{\Gamma(a_{\rm H}+b_{\rm H}+2)\Gamma(a_{\rm H}+2)}{\Gamma(a_{\rm H}+1)\Gamma(a_{\rm H}+b_{\rm H}+3)} = 1\ . \tag{6}$$

Finally, the non-perturbative strange and anti-strange sea distributions in the nucleon can be computed by means of the two-level convolution formulas

$$s^{NP}(x) \;=\; N\int_x^1 \frac{dy}{y} P_H(y)\ s_H(x/y), \tag{7}$$

$$\bar{s}^{NP}(x) \;=\; N\int_x^1 \frac{dy}{y} P_K(y)\ \bar{s}_K(x/y), \tag{8}$$

where the sources $s_H(x)$ and $\bar{s}_K(x)$ are the probability densities of the strange valence quark and anti-quark in the Hyperon and Kaon respectively, evaluated at the hadronic scale Q_0^2 [7]. In principle, to obtain the non-perturbative distributions given by eqs. (8), one should sum over all the strange Kaon-Hyperon fluctuations of the nucleon but, since such hadronic Fock states are necessarily off-shell, the most likely configurations are those closest to the nucleon energy-shell, namely Λ^0K^+, Σ^+K^0 and Σ^0K^+, for a proton state. For the sake of simplicity, we will only consider a generic Kaon and Hyperon inside the proton.

For the $s_H(x)$ and $\bar{s}_K(x)$ probability densities in eqs. (7) and (8) we also used the simple forms

$$s_H(x) \;=\; \frac{1}{\beta(a_{sH}+1, b_{sH}+1)} x^{a_{sH}}(1-x)^{b_{sH}}\ ,$$

$$\bar{s}_K(x) \;=\; \frac{1}{\beta(a_{sK}+1, b_{sK}+1)} x^{a_{sK}}(1-x)^{b_{sK}}\ , \tag{9}$$

according to the valon model. The coefficients a_{sK}, b_{sK}, a_{sH}, b_{sH} in eqs. (9) have to be determined by comparison to experimental data.

III. COMPARISON WITH DATA

In order to fix the coefficients of the model, we compare with the s and $\bar{s}$ parton distribution functions[15] given in Ref. [6], which have been recently obtained in a global fit to DIS data. The comparison has been done by means of a simultaneous least square fit of the model to $xs(x)+x\bar{s}(x)$ and $xs(x)-x\bar{s}(x)$ at $Q^2 = 20$ GeV^2. The results of the fit are shown in Figs. (2) and (3) and in Table I.

The procedure of the fit was as follows: *i)* a set of initial values for the parameters was chosen and the non-perturbative s^{NP} and $\bar{s}^{NP}$ strange quark distribution functions were calculated according to eqs. (7) and (8). Then *ii)* the s^{NP} and $\bar{s}^{NP}$ distributions were evolved from Q_0^2 up to $Q^2 = 20$ GeV^2 and the squared distance

$$\mathcal{S}^2 \;=\; \sum_{i=1}^{n}\left[\frac{\left(y_d(x_i)-y_d^{th}(x_i)\right)^2}{\sigma_d^2(x_i)} + \frac{\left(y_s(x_i)-y_s^{th}(x_i)\right)^2}{\sigma_s^2(x_i)}\right] \tag{10}$$

was calculated. In eq. (10), $y_k(x_i) = xs^{NP}(Q^2,x_i) \pm x\bar{s}^{NP}(Q^2,x_i)$ and $y_k^{th} = xs(Q^2,x_i) \pm x\bar{s}(Q^2,x_i)$, with index $k = d,s$ refering to the difference and the sum respectively. An arbitrary error $\sigma^2_{d/s}(x_i)$ corresponding respectively to 10% of the value of the difference and the sum at x_i has been considered to perform the fit. Finally a new set of parameters was chosen and the procedure has been repeated until a minimum in $\mathcal{S}^2$ was reached.

TABLE I: Coefficients for $s(x)$ and $\bar{s}(x)$ obtained from simultaneous fits to the strange parton distributions funcions in the proton as given in Ref. [6]. $a_H = 2.889$ is fixed by the requirement of momentum conservation given by eq. (6).

b_H	1.563	±0.166
a_K	2.403	±0.127
b_K	4.164	±0.188
a_{sH}	0.669	±0.052
b_{sH}	8.539×10^{-5}	±0.087
a_{sK}	23.203	±0.085
b_{sK}	0.602	±0.002
N	0.019	0.001

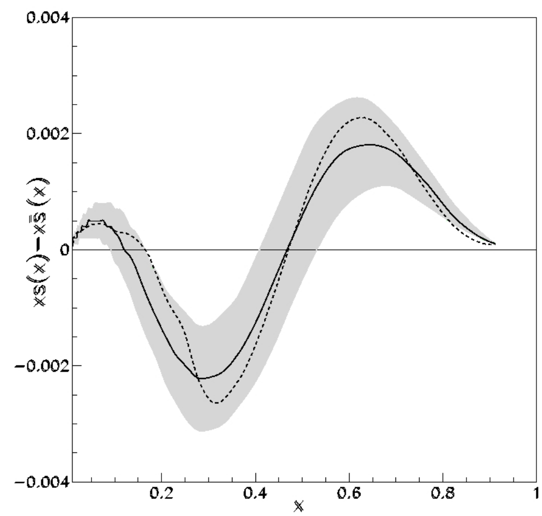

FIG. 2: $xs(x) - x\bar{s}(x)$ at $Q^2 = 20$ GeV^2. Dashed line: the asymmetry obtained in Ref. [6]. Full line: the result of our fit. The shadow area is the uncertainty of the fit.

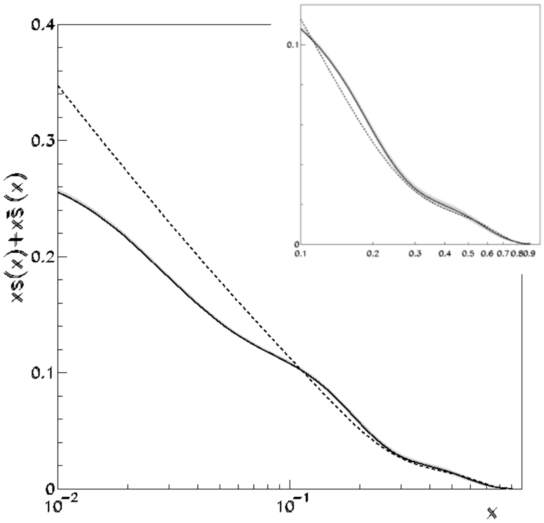

FIG. 3: $xs(x) + x\bar{s}(x)$ at $Q^2 = 20$ GeV^2. Dashed line: the distribution obtained in Ref. [6]. Full line: the result of our fit. In the insert is shown the result of our fit for $0.1 < x < 1$. The uncertainty of the fit is represented by the shaded area.

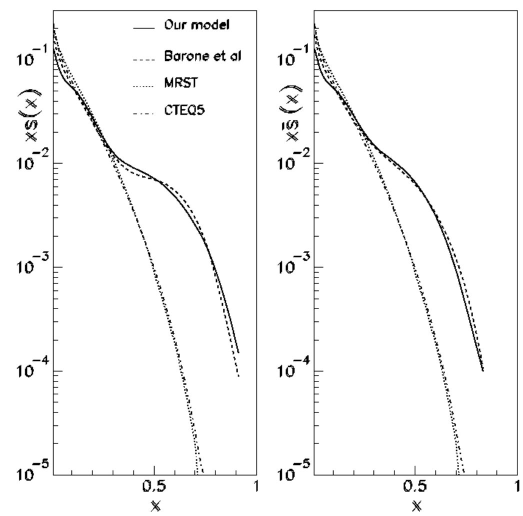

FIG. 5: Strange (left) and anti-strange (right) quark distributions in the proton at $Q^2 = 20$ GeV^2. Our model compared to the V. Barone *et al.* [6], MRST [13] and CTEQ5 [14] strange parton distribution functions.

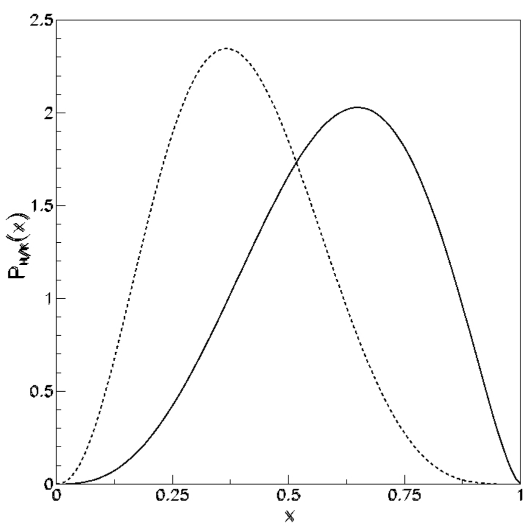

FIG. 4: Full line: Hyperon probability density in the $|KH\rangle$ Fock state of the proton. Dashed line: Kaon probability density in the $|KH\rangle$.

The package MINUIT has been used to perform the fit. Notice also that the QCD evolution of the combination $s + \bar{s}$ depends on the whole set of parton distribution functions in the proton, for which we used the pdf's of Ref. [6].

The best fit has been obtained using $Q_0 = 0.3$ GeV as the starting point for QCD evolution. As can be seen in Figs. (2) and (3), the model represents fairly well the strange parton distributions found in Ref. [6] for $x \gtrsim 0.1$, whereas for smaller values of x our results are below the results of the global fit of Ref. [6]. This can be due to a deficit in the content of gluons, as seems to be indicated by the fact that a good fit is only obtained for extremely low values of Q_0.

Concerning the model itself, the Kaon and Hyperon distributions functions in the $|KH\rangle$ Fock state of the proton are displayed in Fig. (4). The momentum carried by the Hyperon in the $|KH\rangle$ Fock state is $xP_H(x) = 0.6$ while for the Kaon we obtained $xP_K(x) = 0.4$, agreeing with the common intuition that the Hyperon carries more momentum than the Kaon in the $|KH\rangle$ component of the proton wave-function.

In Fig. (5) the strange and anti-strange quark distributions at $Q^2 = 20$ GeV^2 are shown and compared to the xs and $x\bar{s}$ distributions found in Ref. [6]. We also compare to the MRST [13] and CTEQ5 [14] strange quark pdfs, which have been determined imposing $s = \bar{s}$. As shown in the figure, while our strange quark and anti-quark pdfs and those of Ref. [6] are consistent in the full range $0.01 < x < 1$, they deviate from the behavior shown by the MRST and CTEQ5 sets at $x \gtrsim 0.3$.

IV. CONCLUSIONS

In this paper we have presented a model for the non-perturbative structure of the strange sea of the proton. In the model, the non-perturbative s^{NP} and $\bar{s}^{NP}$ intrinsic sea quark distributions of the proton are given in terms of a convolution of Hyperon and Kaon probability densities

and valence quark distributions inside a $|KH\rangle$ component of the proton wave function. This naturally generates an asymmetry in the momentum distributions of the strange and anti-strange quarks in the proton, since the Hyperon, being heaviest than the Kaon, carries more momentum in the $|KH\rangle$ wave funtion component. The model depends on eight parameters which have to be fixed by fits to experimental data.

Parameters of the model have been fixed by fits to the strange quark distributions found in a recent global fit to DIS data [6]. As shown in section III, the model describes qualitatively well the behavior of the $s-\bar{s}$ as well as $s+\bar{s}$ distributions, being this agreement better in the region $x \gtrsim 0.1$. For lower x, the $s+\bar{s}$ distribution is below the corresponding curve given by the distributions of Ref. [6]. The probability of the $|KH\rangle$ fluctuation of the proton is about 0.02%, as given by the parameter N.

The fact that the model does not describe well the $s+\bar{s}$ distribution at $x < 0.1$ is expected by several reasons. First of all, the parton distributions found in Ref. [6] were determined in a global fit to DIS data, instead our s and $\bar{s}$ distributions have been determined by fits to the $s-\bar{s}$ and $s+\bar{s}$ distributions found in [6]. This restrict the space of parameters allowed to the fit. Second, the gluon distribution found in Ref. [6] seems to be insufficient to generate enough $s/\bar{s}$ quarks at low momentum, as evidenced by the fact that while the $s-\bar{s}$ distribution is well described in the whole range $0 < x < 1$, the $s+\bar{s}$ is not. This could also explain why a good fit is obtained only for extremely low values of Q_0, the scale at which perturbative QCD evolution starts. And third, a meaningful comparison of the model has to be done through a global fit to experimental data.

Notice also that no NNLO effects have been included in the QCD evolution of the strange parton distributions. The inclusion of those effects should produce a slightly bigger non-perturbative contribution to the proton wave funtion to compensate the opposite asymmetry which arises at NNLO [10].

Finally we would like to emphasize that the model presented here can be taken as a phenomenologically motivated alternative for the description of the input strange and anti-strange quark distributions used in fits to experimental data. Notice that the model allows for a full representation of the non-perturbative processes inside the proton in terms of well known mechanisms such as the splitting of quarks and gluons and recombination, which after all must account for the dynamics of the proton as a bound state. Another interesting aspect of the model is that it can shed light on the parton structure of real Kaons and Hyperons, since the structure of the strange sea of the proton is related to the strange valence quark distributions at a low Q^2 scale of the former strange mesons and baryons.

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